

**OPTIMAL FUND ALLOCATION FRAMEWORK FOR  
PRIORITIZING HIGHWAY REHABILITATION PROJECTS:  
A QUANTITATIVE ANALYSIS**

A Thesis

by

ANKIT JOSHI

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Chair of Committee,	Kunhee Choi
Committee Member,	Edelmiro Escamilla
	Jun Hyun Kim
Head of Department,	Joseph P. Horlen

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## **ABSTRACT**

The transportation infrastructure system in the United States is aging and insufficient to serve the current needs of a growing population. Major highways have already exceeded their life expectancy. Therefore, state transportation agencies need to restore existing transportation networks across the nation. Penetrating to the second layer of the issue, there are many highways to rehabilitate, but funds are limited. This demands efficient allocation and prioritization of projects.

The lack of analytical methods for fund allocation and project prioritization has always been a challenge for transportation agencies. To address this issue, this research is intended to develop a quantitative approach to prioritizing capital projects. The major objectives of this research are (a) to highlight the limitation of existing fund allocation and prioritization methods and (b) to create an effective quantitative model for prioritizing projects for transportation agencies.

The pertinent literature review of monthly Texas Department of Transportation reports was accomplished to select three real-time highway projects from Texas. The information retrieved from the reports includes average annual daily traffic, total project cost, length (in miles), and crash rate information for the selected project. First, information was analyzed to calculate accident savings using cost-benefit analysis and ranked according to their cost to benefit ratio. The same data was processed to reduce

envy and allocate funds fairly on the basis of three criteria (i.e., cost, safety, and traffic congestion) using the fair division method algorithm coded on a Matlab framework. Last, results from the previous two methods were analyzed and integrated using the analytical hierarchy process to generate a common result. The results of the research reveal that the combination of the cost-benefit analysis, the fair division method, and the analytical hierarchy process can be a promising tool, as it is not only effective to prioritize projects on their merits but also helps to minimize envy among participants during fund allocation.

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# **CHAPTER I**

## **INTRODUCTION**

### **1.1 Background**

Most of the highways in the US have exceeded their design life and demand urgent rehabilitation. Moreover, the efficiency of the U.S. transportation network system is adversely impacted by the increasing population. To exacerbate the situation, limited funding for maintenance and construction of highways undermines the financial development of the country and the quality existence of the general population (Chang, Montes, Taboada, & Espiritu, 2014). In the context of Texas, per recent projections, the Texas population is expected to reach more than 35 million by 2040 (Transportation Funding, 2012-2013). To restore the nation's highways, a significant amount of money needs to be raised, "In 2009, the 2030 committee, a group of Texas business, academic, and civic leaders, determined that the state needed to invest some \$315 billion over the next two decades to maintain the existing transportation infrastructure, prevent worsening congestion in urban areas, and ensure rural mobility and safety" (Transportation Funding, 2012-2013). According to the Agency Financial Report for the fiscal year 2013 (U.S. DOT, 2013), the gross cost incurred in surface transportation was \$60.70M.

As an attempt to rejuvenate existing transportation systems, the Obama administration allotted \$80 billion of federal money to improve highway infrastructure (President's

Fiscal Year 2014 budget report, U.S. DOT, 2013). Of \$80 billion, \$50 billion was requested for immediate investment. Not all future demands can be addressed in the available funding. This necessitates the shrewd usage of restricted assets by streamlining the level of the capital with the right blend of quantitative methodologies to preserve existing transportation systems.

## **1.2 Need of Efficient Analytical Project Prioritization Tool**

The state transportation agency (STA) requires a tool that can help to prioritize the project and simultaneously reduce envy in the fair division of funds among all of the participants. The prioritization procedure includes numerous technical and non-technical factors in consideration such as cost, safety, reduction in traffic congestion, and social-political issues. Currently, there is no analytical tool that embeds all factors to generate accurate results. However, a tool can be created that enfolds most of the major criteria to give acceptable results, especially for maintenance and rehabilitation projects and the major factors or criteria: costs, safety, traffic congestion, and travel time (i.e., user benefits). These criteria are quantifiable in terms of financial advantages, which assist STAs to reach a conclusion in a more confident manner. Therefore, with the help of two or more qualitative approaches such as cost-benefit analysis (CBA), the fair division method (FDM), and the analytical hierarchy process (AHP), desired results could be achieved.

## **CHAPTER II**

### **RESEARCH SCOPE AND SIGNIFICANCE**

#### **2.1 Gaps in Existing Knowledge**

Poorly managed highway infrastructure is one of the public issues in the United States even though highway infrastructure influences the national economy in many ways (Tare, 2014). Criticality of the situation can be understood by the prompt investment of \$80 billion federal funds for highway restoration and development. Despite this, it is insufficient to meet the present needs. At present, STAs are utilizing methodologies, for example, CBA, which takes only cost or monetary benefits into consideration. It converts accident savings and travel time saved into cost/savings. Henceforth, the project with the most financial advantages will be selected, and funds will be assigned to it. Aside from this, the process of dispersion of funds based on size of county or district prompts unfair allocation of funds, which ignites envy among counties or districts.

There have been many attempts to establish mathematical tools to reinforce decision-making and the fund allocation process. However, apart from the abovementioned limitations, existing methods have one more major limitation. They can compare only two projects at a time. For more than two projects, results are inaccurate. Therefore, there is an urgent need for a tool that envelops major criteria, compares more than two projects, and minimizes envy among participants in the fair division of funds.

To provide a reliable fund allocation and project prioritization model, one of the approaches is to employ a combination of quantitative analysis methods such as CBA, FDM, and AHP. CBA is a quantitative approach to measuring the financial desirability of any project and a great tool to help in making decisions for allocating resources (Gherghinescu & Bandoi, 2010). FDM focuses on freeness, efficiency, and equitability of allocation of funds. AHP is one of the most commonly used methodologies to evaluate and quantify subjective judgment (Gonzalez et al., 2013). It is considered one of the most effective decision-making methods that can also be used to rank projects according to their viability (Amponsah, 2013).

## **2.2 Problem Statement and Research Objectives**

Fair allocation of funds and project prioritization are very important steps for STAs and their beneficiaries (i.e., county, district, or state). However, it is a very daunting task for STAs because of limited funding and lack of effective analytical tools. Although there are some quantitative methods on which transportation agencies rely for funding allocation and ranking projects, most of them do not generate accurate results. The following are the problems in existing practices that have been observed: (a) existing methods utilize formulas based on the population size and performance criteria, which lead to unfair division of funds; (b) existing methods are focused on a single criterion such as financial benefits; (c) current methods ignore socioeconomic issues such as fair division or minimizing envy, which is the vital part of decision-making; and (d) the accuracy and reliability of the existing quantitative tool is questionable. To manage these

issues, the key objective of this research is to create a custom quantitative model for U.S. transportation agencies that fairly allocates funds by minimizing envy and prioritizing projects logically.

### **2.3 Hypothesis**

This research uses three different quantitative analysis methods (i.e., CBA, FDM, and AHP). These methods take different mathematical equations, factors, and criteria into consideration, which were identified in the literature review. None of the methods has any element in common. However, when used unanimously, an effective mathematical tool can be developed to solve the problem related to funding allocation and prioritization of the project.

### **2.4 Limitations**

This research is an extension of the studies done to date to reduce envy during fund allocation and prioritization of projects. This topic is still under research across the world. This research focuses on highway rehabilitation projects. Research was conducted under the following assumptions and limitations:

1. Considering TxDOT has a single pool of funds for all type of transportation projects;
2. The highway rehabilitation projects under study have a value less than \$10 M in total project cost; and
3. Selected samples are less than 10 centerline miles in total project length.

## **CHAPTER III**

### **LITERATURE REVIEW**

#### **3.1 Introduction**

A review of the pertinent literature was accomplished to gain more insight about the recent trends and methodology used by TxDOT and other transportation agencies around the United States to prioritize resources and projects. Specifically, the literature review was conducted to identify prominent factors affecting fund allocation for highway projects and to comprehend quantitative methods such as CBA, FDM, and AHP that can be adopted as a potential way to design a new single framework for prioritizing projects and resources.

#### **3.2 Current Scenario**

Most state agencies, including TxDOT, use CBA and weighted formulas that are based on population, safety, and other factors (Mathur, 1996). Factors are critically considered and evaluated by highway agencies during decision making. Moreover, in the United States, transportation projects are also influenced by intergovernmental relations and financing mechanisms. Therefore, some county can pull in a big part of the budget because the funding channels through the higher governmental level (Weiner, 1999). This demands the strict need of utilizing formulas for fund distribution so that states or districts do not get the larger share of funds through lobbying (Lee, 2000).

### **3.3 Current Projection Selection Criteria**

The following steps are involved in the TxDOT current project selection criteria (TxDOT, 2012):

- **Identification of Needs**

Once a need has been identified, the projects are requested through TxDOT local offices or the Metropolitan Planning Organization (MPO; TxDOT, 2012), followed by project selection based on state transportation plan goals such as safety, maintenance and preservation of the existing system, congestion relief, access and mobility, efficient system management, and operations.

- **Development of Successful Financial Plans**

The sources of funding include local funding, state funding, federal funding, debt financing pass-through financing, toll equity, and public-private partnership (TxDOT, 2012). According to a 10-year project development and construction plan called the Unified Transportation Program, there are 12 funding categories as follows (Statewide Preservation Program, 2007):

1. preventive maintenance and rehabilitation,
2. metropolitan and urban area corridor projects,
3. non-traditionally funded transportation projects,
4. statewide connectivity corridor projects,
5. congestion mitigation and air quality improvement,
6. metropolitan mobility/rehabilitation,



7. bridges,
8. safety,
9. transportation enhancements,
10. supplemental transportation projects,
11. district discretionary, and
12. strategic priority.

- **Initiation of Planning**

This is the stage of money involvement. All projects compete for the funding and sometimes a few share common funding sources.

- **Progress in Project Development**

An essential element of this step is public involvement, where citizens give their inputs on the decision-making process by participating through public hearings and gatherings.

- **Construction**

After all of the above steps, the construction contract for the project is awarded by competitive bidding and the lowest bidder is awarded the contract.

### 3.4 Existing Analytical Tools and Their Application

#### 3.4.1 Fair Division Method

As discussed, current practice does not ensure the fair distribution of resources. To overcome this shortcoming, a fair division transportation allocation model (FDTAM) is proposed as an alternative to fairly distribute limited funds among the agencies competing for funding. This method is more focused on the objective to minimize envy that has generated due to budget constraints (Chang et al., 2014).

There are four characteristics of the fair division method: proportionality, efficiency, envy-freeness and equitability (Albitres, Krugler, Ibarra, & Montes, 2012).

- **Proportionality:** Each participant receives an equal share (i.e.,  $1/n$  of the total funds).
- **Efficiency:** All of the allocations are equal. No allocation is better than another .
- **Envy-freeness:** It does not imply that all participants will receive equal amounts but refers to the a bidder or participant believing that he or she has received sufficient funds per his or her requirement.
- **Equitability:** Every participant obtains the same amount according to his or her respective valuation. Thus, every participant gets the same “value.”

Among these characteristics, only envy and proportionality can be explained mathematically. There is no different mathematical expression for proportionality. It is covered and defined under the envy mechanism.

Envy is the ratio of allocated funds to expected funds. It is this function that must be minimized to provide a fair share to each of the participants.

Mathematically, envy can be expressed as:

$$\min \left[ \sum_{i=1}^n \epsilon_{ij} (X_j) \right]$$

$$|\rho_1 - \rho_2|, \text{ if } (\rho_1 - \rho_2) < 0 \\ 0, \text{ otherwise}$$

And,

$$\rho = \frac{\text{Total Allocation Funds}}{\text{Total Value Of Expected Funds}}$$

$\rho_i$  = Assigned to expected funds ratio of *i* th

$\rho_j$  = Assigned to expected funds ratio of *j* th

$\epsilon_{ij}$  = Envy sensed by *i*th with respect to *j*th

*n* = Total number of participants

(Albitres et al., 2012).

### 3.4.2 Cost Benefit Analysis

According to the publication “Introduction to cost-benefit analysis, Part IV, applications to highway projects” (Harberger, 2009), all of the highway projects should be carried out based on potential benefits associated with the project.

A benefit-cost analysis is a systematic evaluation of the economic advantages (i.e., benefits) and disadvantages (i.e., costs) of a set of investment alternatives. Typically,

two or more alternatives are compared. It shows incremental differences between provided alternatives. CBA gives a clear picture of benefits if a particular option is undertaken over another. It converts the outcome of investment into monetary terms and draws the benefits that will accrue over the useful period of the project. For transportation projects, many factors can be monetized such as travel time costs, vehicle operating costs, and reduced accident rates.

As a decision-making tool, CBA has a myriad of applications in various sectors such as education, health, and safety including the transportation sector (Fuguitt & Wilcox, 1999). Effective allocation of funding resources necessitates a certain mathematical tool to prioritize projects. Mathematical tools ensure more logical and unbiased outcome (Annes et al., 2006). CBA is one of the tools that can be adopted to compare cost-benefits associated with several projects. Many agencies use CBA to make a logical selection and assess financial investment related to it.

According to Kornhauser (2000), concerning justifying cost-benefit analysis, “CBA is both a theory and a practice” (p. 1039). Kornhauser split CBA into three parts that can be applied to allocate limited resources for infrastructure improvement projects:

1. CBA can be used to develop correlations among fundamental preferences and a ranking in terms of money or policies,
2. identification of all of the entities (real and conceptual), and
3. applying formal theory (Kornhauser, 2000).

Cost-benefit analysis is the ratio that expresses benefits provided by the project to the cost incurred by it. Both the benefits and cost are expressed in the present value.

- If  $\frac{Benefit}{Cost} > 1$ , then benefits outweigh cost;
- If  $\frac{Benefit}{Cost} < 1$ , then cost outweighs benefits;
- If  $\frac{Benefit}{Cost} = 1$ , then they are the same

$$PV = \frac{AC_{Y_i}}{(1+r)^{y_i-y_0}} \text{Where:}$$

PV = Present value

r = Discount rate

$y_i$  = Year in which the cost or benefit occurs

$y_0$  = Year of analysis

(transportation, 2015).

$$BCR = \frac{PV_{benefits}}{PV_{costs}}$$

Where:

$PV_{benefits}$  = Present value of benefit

$PV_{costs}$  = Present value of Cost

However, CBA is not a perfect tool for analysis and the selection process. Evidently, social factors such as fair allocation and minimizing envy, which are the critical parts of

decision-making, cannot be monetized by CBA. Hence, this method gives only a single dimension analysis, which can affect the accuracy of the result.

### **3.4.3 Analytic Hierarchy Process**

The result generated by CBA and FDM cannot be compared directly to rank projects, as both methods are independent and have different objectives. To provide the common analytical base to integrate results of CBA and FDM, the analytic hierarchy process (AHP) also has been incorporated into the research. AHP has been used in different disciplines to assign ranking and prioritize projects. Its ability to handle both qualitative and quantitative data makes it an ideal method. For agencies to have a clear vision about executing the prioritizing project requires a specific objective and scientific approach (Amponsah et al. 2013). The fundamental logic of AHP is to fragment a large, complex task into smaller, manageable subtasks. AHP is built on pair-wise comparison where each pair-wise comparison is carried out among two alternatives at once, and relative value is assigned, which is followed by use of a priority vector for given alternatives that is generated from the synthesis of a pair-wise comparison (Amponsah et al. 2013). Using AHP, selected projects can be ranked in descending order with the most viable at the top and least at the bottom. The calculation can be done manually or using software such as “Super Decision” (Amponsah et al. 2013). Due to its many successful applications and its simplicity, the AHP was selected as one of the methods for this research.

## **CHAPTER IV**

### **METHODOLOGY**

#### **4.1 Introduction**

In response to the challenges STAs are facing and addressing the shortcomings of the existing fund allocation and project prioritizing methods, a quantitative analysis was accomplished. This research applies a custom-built quantitative model for fund allocation and project prioritization. This research model was devised to compensate for shortcomings of existing STA practices. The research analyzes information gathered from the TxDOT database. Information includes details such as average annual daily traffic (AADT), total construction cost, length (in miles), and crash rates for three real-time highway projects located in different parts of Texas. Collected data was analyzed using CBA, where accident savings (i.e., benefit) and cost were calculated in 2014 U.S. dollar values for each project. These cost and benefit values for projects are then utilized to calculate the cost to benefit ratios for respective projects. Finally, projects are ranked in descending order of cost to benefit ratio. CBA checks the financial feasibility of the project.

Further, in an attempt to reduce envy, project samples were refined using FDM on a Matlab framework. A literature review was undertaken to understand the application of the fair division method. The last step involves allocation of final ranking to the project samples according to AHP using Super Decision software. AHP integrates the two

independent results of CBA and FDM to determine a common result and prioritize projects according to their viability.

## **4.2 Experimental Procedure**

The principal objective of this research is to provide a transportation agency with a tool to minimize envy and promote fairness in the allocation of funds. Research is comprised of three phases. Phase I includes a case study followed by cost-benefit analysis. Phase II is comprised of analysis by the fair division method and phase III embraces rank allocation using AHP analysis. Figure 1: shows the flowchart of the research methodology.

### **4.2.1 Phase I**

#### **4.2.1.1 Case Study**

After a pertinent literature review, information was collected related to three highway projects located in the state of Texas. Data was gathered from the TxDOT monthly report. To make samples that are more diverse, they were collected from three different counties (i.e., Collin, Harris, and Dallas). Moreover, all three selected highway projects were distinct in terms of their categories. The sample from Collin County is state highway SH 5, US 90 A. The sample from Harris County is a national highway and IH 35 E from Dallas County is an interstate highway.



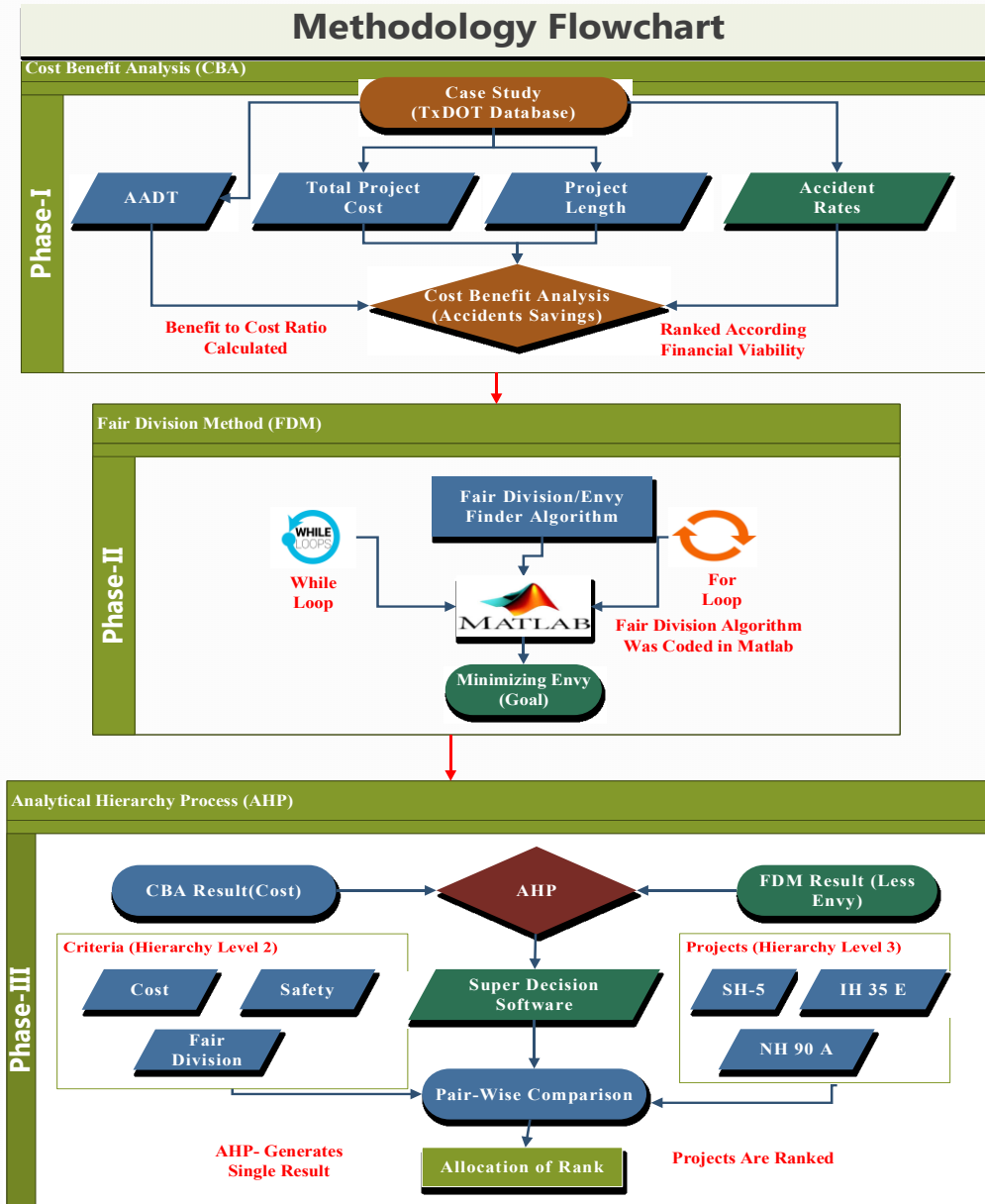


Figure 1: The Flow Chart for the Methodology

The collected data are comprised of project length (in miles), project duration (in days), project construction cost (in 2013 U.S. dollars), AADT for 2012, and traffic crashes (2012). Data accumulated was utilized to calculate accident savings (benefits) and costs associated with project samples using CBA to perceive their respective monetary advantages.

#### **4.2.2 Cost Benefit Analysis**

Data accumulated was utilized to determine accident savings (benefits) and cost for project samples by using CBA to perceive their monetary advantage (transportation, 2015). The following steps were implemented to determine the cost to benefit ratio.

##### **4.2.2.1 Step I: Cost**

Table 1: Project Information Located in Different Districts of Texas (TxDOT, 2014).

S.No.	Project ID	Highway	County	Project Length (in miles)	Project Duration (in contract working days)	Total Project cost (in 2013 U.S. dollars)
1	NH 2013 (448)	SH 5	Collin	1.815	105	\$1,311,303.79
2	NH 2013 (061)	US 90 A	Harris	2.762	132	\$2,433,336.71
3	IM 0356 (435)	IH 35 E	Dallas	3.39	119	\$1,743,690.74

##### **4.2.2.1.1 Present Value of Cost**

As mentioned, the total cost of the projects is available in 2013 U.S. dollar values (Table 1:). However, we are doing the calculation for the year 2014. Therefore, costs were

converted into 2014 U.S. dollar values using the present value formula. The calculation was completed based on following formula given by the U.S. Department of Health and Human Services (2014):

$$PV = \frac{AC_{Yi}}{(1 - r)^{yi-y_0}}$$

Where:

PV = Present value

r = Discount rate

$y_i$  = Year in which the cost or benefit occurs

$y_0$  = Year of analysis

According to Standard and Poor's financial agencies, LLC. (Poor's, 2014), the discount rate is taken as 1.58%. The present values of the costs for each project are listed in Table 2: below.

Table 2: The Present Value of Cost for Each of the Projects

S.No.	Project ID	Highway	County	Total Project cost (in 2013 U.S. dollars)	Present Value of Cost (2014 dollars)
1	NH 2013 (448)	SH 5	Collin	1,311,303.79	1,332,219.638
2	NH 2013 (061)	US 90 A	Harris	2,433,336.71	2,471,783.43
3	IM 0356 (435)	IH 35 E	Dallas	1,743,690.74	1,771,241.05

#### **4.2.2.2 Step II: Benefits**

Benefits can be defined as the induction of well-being (change in individual life) due to highway rehabilitation (Kornhauser, 2000). The main reason for pursuing a highway improvement project is to relieve traffic congestion, save travel time during peak hours, and reduce accident rates. This is calculated as road user cost. Road user cost is not tangible but can be monetized by an infusing concept of opportunity cost. Opportunity cost is the time motorists could have utilized doing something else important.

For this research, we considered commuter safety as a most important and critical factor because the cost associated with accidents consumes the major piece of agencies budgets. Moreover, accident savings not only involves saving money that will be incurred by avoiding crashes; it also concerns saving commuters' lives, which makes it a major factor in the decision making and prioritization process. Hence, only accident savings is included as the decisive factor.

Calculating accident benefits is a multi-step process. The calculation mechanism is explained in the following steps:

##### **4.2.2.2.1 Accident Savings**

- **Annual Average Daily Traffic**

In simple terms, AADT is a number that is used in the transportation planning and engineering sector to measure the annualized average 24-hour volume of vehicles on a

given length of a highway. Mathematically, it is the total volume of vehicular traffic on a highway segment for a year divided by 365 days (AADT, 2013).

The following Table 3: contains data from the district traffic maps developed by the transportation planning and programming division of TxDOT (TxDOT, 2012).

Table 3: Details of the Data Collected on AADT for Each of the Projects

S.No.	Project ID	Highway	County	From	To	AADT 2012 (in vehicles per hour per lane)
1	NH 2013 (448)	SH 5	Collin	SP 399	Wilson Creel Bridge	19,400.00
2	NH 2013 (061)	US 90 A	Harris	IH 45 Valley View	Avenue W	26,000.00
3	IM 0356 (435)	IH 35 E	Dallas	Lane	Whit lane	60,000.00

- **Vehicle Miles Travelled**

As AADT data is collected, it is converted into vehicle miles travelled (VMT), which can be defined as the amount of traffic on a particular section of highway. For further calculation, the number of vehicles on a selected length of a highway sample is needed. Therefore, AADT is converted to VMT, as AADT is the rate of flow of traffic on a highway. Mathematically, VMT can be explained as below (Annes et al., 2006):

$$VMT = \frac{Length * AADT * 365}{100e6}$$

Substituting all of the data in the above formula for project samples, VMT was calculated.

1. VMT for SH 5 = 0.13
2. VMT for US 90 A = 0.26
3. VMT for IH 35 E = 0.74

- **Crash Rate or Accident Rate**

The crash rate for a highway section is defined as the total number of crashes occurred with respect to the total number of vehicle miles traveled. To calculate the crash rate, the report published by TxDOT on statewide traffic crash rates has been used (TxDOT, Statewide Traffic Crash Rates, 2012). According to the report:

- For the U.S. highway system: traffic crashes per 100 million vehicle miles = 145.69.
- For the interstate highway system: traffic crashes per 100 million vehicle miles = 108.35.
- For the state highway system: traffic crashes per 100 million vehicle miles = 195.95.

Mathematically, the crash rate can be expressed as VMT multiplied by traffic crashes.

$$\text{Crash rate} = \text{VMT} * \text{Traffic Rates}$$

Therefore, crash rates for all the projects are as follows:

1. Crash rate for SH 5 =  $0.13 * 195.95 = 25.47$
2. Crash rate for US 90 A =  $0.26 * 145.69 = 37.87$
3. Crash rate for IH 35 E =  $0.74 * 108.35 = 80.18$

- **Crash Modification Factor**

A crash reduction factor (CRF) is the percentage of crash reduction that might be expected after implementing a given improvement at a specific site. Mathematically, the crash modification factor (CMF) is calculated as (Federal Highway Administration, 2010):

$$CMF = 1 - (CRF/100)$$

The average value for CRF in Texas is 41.4% with a maximum of 91% and a minimum of 10% with a standard deviation of 16.7 (Reddy, 2007). For this research, a CRF of 41.4% was used; to eliminate statistical bias, it is assumed to be the same for every project. Substituting values in the above formula, we obtain:

$$CMF = 1 - (41.40/100) = 0.586$$

- **Modified Crash Rate**

The modified crash rate (Table 4:) is calculated by multiplying crash rate by crash modification factor (administration, 2011).

Mathematically,

$$\text{MCR} = \text{CMF} * \text{crash rate}$$

Substituting values:

1. Modified crash rate for SH 5 =  $0.586 * 25.47 = 14.93$
2. Modified crash rate for US 90 A =  $0.586 * 37.87 = 22.19$
3. Modified crash rate for IH 35 E =  $0.586 * 80.18 = 46.99$

Table 4: The Modified Crash Rates for Each of the Projects

S.No.	Project ID	Highway	County	Crash or Accident Rate	Crash Modification Factor	Modified Crash Rate
1	NH 2013 (448)	SH 5	Collin	25.47	0.586	14.93
2	NH 2013 (061)	US 90 A	Harris	37.87	0.586	22.19
3	IM 0356 (435)	IH 35 E	Dallas	80.18	0.586	46.99

- **Crashes Avoided**

After calculating crash modification rate, crashes avoided is calculated. Crashes avoided (Table 5:) is the difference between original crash rate and the modified crash rate (Annes et al., 2006).



Table 5: Total Crashes Avoided for Each of the Projects

S.No.	Project ID	Highway	County	Crash or Accident Rate	Crash Modification Factor	Crashes Avoided
1	NH 2013 (448)	SH 5	Collin	25.47	14.93	10.54
2	NH 2013 (061)	US 90 A	Harris	37.87	22.19	15.68
3	IM 0356 (435)	IH 35 E	Dallas	80.18	46.99	33.19

- **Crashes Cost**

Crash cost (Table 6:)can be calculated by a simple formula, which is as follows (Annes et al., 2006). Per 2005 crash cost data, accident costs in Texas were \$34M. Crash cost involves safety equipment expenditure, uncompensated property damages, medical treatment cost, and insurance deductible.

$$\text{Crash Cost} = \text{Accident Rate} * \text{AADT} * \text{Project Length} * \text{Accident Costs}$$

Table 6: The Crash Cost (2005 Dollar) for Each of the Projects

S.No.	Project ID	Highway	County	Project Length (in miles)	AADT 2012	Crash or Accident Rate	Crash Cost (in 2005 dollars)
1	NH 2013 (448)	SH 5	Collin	1.815	19,400	25.74	3,000
2	NH 2013 (061)	US 90 A	Harris	2.762	26,000	37.87	9,300
3	IM 0356 (435)	IH 35 E	Dallas	3.39	60,000	80.18	54,000

- **Cost/Crash**

Cost/crash can be defined as the ratio of total crash cost for each project and their respective total crashes (Annes et al., 2006). Table 7: shows the cost/crash for each of the projects.

Table 7: The Cost per Crash (2005 Dollars) for Each of the Projects

S.No	Project ID	Highway	County	Vehicles Miles Travelled (VMT) (in 100 millions)	Crash or Accident Rate	Crash Costs (in million and 2005 dollars)	Cost/Crash (in 2005 dollars)
1	NH 2013 (448)	SH 5	Collin	0.13	25.74	0.03	\$116,501.16
2	NH 2013 (061)	US 90 A	Harris	0.26	37.87	0.093	\$245,576.97
3	IM 0356 (435)	IH 35 E	Dallas	0.74	80.18	0.54	\$336,368.86

- **Benefits**

Benefits are monetary advantages that might be incurred after rehabilitation of selected samples. Benefits have been calculated by following the formula (Annes et al., 2006).

$$\text{Benefits} = \text{Crash Rates} * \text{VMT} * \text{Cost/crash} * \text{Crash Reduction Rate}$$

Crash reduction is defined as the ratio of crashes avoided and crash rate, which comes out to be 0.42.

Table 8: The Benefits in 2005 Dollar Values for Each of the Projects

S.No.	Project ID	Highway	County	Vehicles Miles	Crash or Accident Rate	Costs/Crash (in 2005 dollars)	Benefits (in 2005 dollars)
1	NH 2013 (448)	SH 5	Collin	0.13	25.74	\$116,501.16	161,392.18
2	NH 2013 (061)	US 90 A	Harris	0.26	37.87	\$245,576.97	1,001,052.00
3	IM 0356 (435)	IH 35 E	Dallas	0.74	80.18	\$336,368.86	8,384,880.61

- **Present Value of Benefits**

The benefits mentioned in Table 8: are in 2005 U.S. dollars, which need to be converted into 2014 U.S. dollar values using the following present value formula (transportation, 2015).

$$PV = \frac{AC_{Yi}}{(1 - r)^{yi - y_0}}$$

Where:

PV = Present value

AC (or AB) = annual cost (or benefit)

r = Discount rate

y<sub>i</sub> = Year in which the cost or benefit occurs

y<sub>0</sub> = Year of analysis

According to Standard and Poor's financial agencies, LLC (Poor's, 2014), the discount rate is taken as 2.97 %. The present values of the costs for each project are listed in Table 9:.

Table 9: The Present Value of Benefits in 2014 Dollar Values for Each of the Projects

S.No.	Project ID	Highway	County	Benefits (in 2005 dollars)	Present Value of Benefits (in 2014 dollars)
1	NH 2013 (448)	SH 5	Collin	161,392.18	\$211,703.60
2	NH 2013 (061)	US 90 A	Harris	1,001,052.00	\$1,313,113.77
3	IM 0356 (435)	IH 35 E	Dallas	8,384,880.61	\$10,998,731.51

#### 4.2.2.3 Step III Cost-Benefit Ratio

Cost-benefit ratio is the ratio of the total present value of costs associated with the project to the total present value of benefits of the same project.

Mathematically,

$$BCR = PV_{\text{BENEFITS}} / PV_{\text{COSTS}}$$

Where:

$PV_{\text{BENEFITS}}$  = Present value of benefit

$PV_{\text{COSTS}}$  = Present value of cost

Referring to Table 1: and Table 9: for values of cost and benefit for each project and substituting them in the above formula:

1.  $BCR_{SH\ 5} = 211,703.60 / 1,332,219.638 = 0.16$
2.  $BCR_{US\ 90\ A} = 1,313,113.77 / 2,471,783.43 = 0.54$
3.  $BCR_{IH\ 35\ E} = 10,998,731.51 / 1,771,241.05 = 6.30$

Table 10: The Cost-benefit Ratios for Each of the Projects

S. No.	Project Name	Benefit/Cost Ratio
1	SH 5	0.16
2	US 90 A	0.54
3	IH 35 E	6.30

#### 4.2.2.4 Step IV Prioritized List According to Cost Benefit Analysis

After CBA calculation (Table 10:), projects have been ranked from higher to lower cost-benefit ratio (see Table 11:).

Table 11: The Prioritized List of the Projects

S. No.	Project Name	Benefit/Cost Ratio
1	IH 35 E	6.30
2	US 90 A	0.54
3	SH 5	0.16

#### 4.2.3 Fair Division Method

FDM is the main highlight of this research. It plays a very crucial role in achieving the objective of the research. FDM deals with the dispersion of funds such that each participant receives a fair share (Chang et al., 2014). Transportation agencies such as

TxDOT have showed a great inclination toward this mathematical model, which is comprised of freeness, efficiency, and equitability.

As discussed in the literature review, current practices employed by transportation agencies for fund allocation prevent fair dispersion of funds. This results in envy among participants. There are some applications of the fair division method and envy finder algorithm, but they cannot be used to compare more than two projects at a given time.

Research focuses on the very novel approach to minimize envy, which is a combination of the sequential allocation model (SAM) and envy finder algorithm (EFA). The model compares all of the projects with the provided decisive factors.

#### **4.2.3.1 Initialize Model**

The following steps have been followed to calculate envy (Chang et al., 2014).

##### **4.2.3.1.1 Step I**

The sequential allocation model involves generation of the set of variables. The first vector, called the row vector, consists of all the available criteria that are essential for making a decision in this research (i.e., safety, cost, and traffic) and the costs associated with them.

$$\mathbf{F} = \begin{bmatrix} f_i \\ \vdots \\ f_m \end{bmatrix}$$

Where:

$F$  = Row vector with all criteria

$f_k$  = Funds associated with all criteria,  $k = 1, 2 \dots m$

Simultaneously, we determine the cost of the entire project with all deciding criteria.

Here, it is assumed that decision makers have access to cost information.

$$\mathbf{C} = \begin{bmatrix} c_{11} & \cdots & c_{1n} \\ \vdots & \ddots & \vdots \\ c_{m1} & \cdots & c_{mn} \end{bmatrix}$$

Where:

$C$  = Matrix that contains the cost of all the proposed highway maintenance projects

$c_{ki}$  = Cost associated with decision criteria  $k$  corresponding to proposed project  $i$ ,  $k = 1, \dots m$  and  $n = 1, \dots n$

Considering the cost matrix and the expected utility, which can be defined as total monetary value, each county expects to receive for project completion, can be calculated.

$$u_i = \sum_{k=1}^m c_{ki}$$

Where:

$u_i$  = Project  $i$ 's fund expectation

$c_{ki}$  = Cost associated with decision criteria  $k$  corresponding to proposed project  $i$ .

#### 4.2.3.1.2 Step II

##### ***Priority Level Matrix***

This is the most important step because sequential allocation is determined by the priority level matrix. This matrix consists of a random weight assigned to the criterion for each project to justify demanded funds. Mathematically, the priority matrix can be defined as:

$$PL = \begin{bmatrix} p_{11} & \cdots & p_{1n} \\ \vdots & \ddots & \vdots \\ p_{m1} & \cdots & p_{mn} \end{bmatrix}$$

Where:

PL = Matrix that contains the priority for all proposed projects

$p_{ki}$  = Priority level of a project  $k$  corresponding to criteria  $i$ .  $k = 1, \dots, m$  and  $n = 1, \dots, n$

#### 4.2.3.1.3 Step III

##### ***Sequential Allocation***

It works on a very simple principle. First, the project with the highest priority number was selected. Once the funds are allocated to this project, its priority becomes zero, and



its allocated cost is deducted from the total fund available. Then the fund is allocated to the project with the second highest priority number and so on. This process is repeated until all the funds are exhausted.

$$U_i = \frac{\mu_i}{u_i}$$

Where:

$\mu_i$  = Actual fund assigned to county  $i$

$u_i$  = County  $i$ 's assigned utility

#### 4.2.3.1.4 Step IV

##### *Envy Finder Algorithm*

Considering the above sequential allocation, if funds are exhausted before county  $i$  obtains its expected funds to rehabilitate its project, then  $\mu_i < U_i$ . That means county  $i$  will feel envy for county  $j$ .

Mathematically, envy can be defined as:

$$\varepsilon_{ij} = \begin{cases} |U_i - U_j|, & \text{if } (U_i - U_j) < 0 \\ 0, & \text{otherwise} \end{cases}$$

Where:

$U_i$  = County  $j$ 's assigned utility

$\mathcal{E}_{ij}$  = Envy sensed by district  $i$  with respect to agent  $j$

Envy sensed by a county can be defined as:

$$E_i = \sum_{j=1}^n \varepsilon_{ij}$$

Where:

$E_i$  = Total envy sensed by agent  $i$

The total envy can be defined as the sum of all envy.

$$\sum E = \sum_{i=1}^n E_i$$

This is the complete mathematical framework for sequential allocation and the envy finder algorithm.

#### **4.2.3.2 Matlab Model**

To achieve an objective of minimizing envy, the above algorithm was coded in Matlab R2015a. The code was specifically designed so that solutions could be generated for  $m$  criteria and  $n$  projects.

Per data calculated during the cost-benefit analysis, total expected fund required for the proposed project is \$5,547,693.81, assuming the total fund available with the transportation agency is \$4,500,000.00.

Appendix 1 shows part of the Matlab framework that has been used in the research. Here, data was defined using code language. Project cost (Table 1:) has been divided equally among the three criteria. All costs are divided into three equal parts. Further, a priority matrix was assigned (Table 21:).

The priority matrix is comprised of numbers that are basically a weight assigned to each criterion for respective projects. The total sum of the numbers adds up to 1. For example, row 1 has 0.53, 0.24, and 0.23, the sum of which equals 1. Algorithm “stop\_flag=0” was defined, which distributes funds among projects until available funds become zero.

Appendix 2 shows the application of while loop in the Matlab. This loop used a priority matrix to distribute funds per assigned priority number. In the process, the funds were distributed first to the project with the highest priority number. Once the funds are transferred to that project, its priority number became zero and then funds were assigned to the project with the second highest priority number. This cycle goes on until available funds become zero. Matlab generated eight iterations for sequential allocation of funds. All iterations (Table 12: to Table 19:) are as follows:

Table 12: Iteration: 1

S.No.	Utility	Assigned Value	Expected Value
SH- 5	1.00	444073.21	1332219.64
US- 90A	0.00	0.00	2471783.43
IH- 35E	0.00	0.00	1743690.74

Table 13: Iteration: 2

S.No.	Utility	Assigned Value	Expected Value
SH- 5	1.00	444073.21	1332219.64
US- 90A	1.00	823927.81	2471783.43
IH- 35E	0.00	0.00	1743690.74

Table 14: Iteration: 3

S.No.	Utility	Assigned Value	Expected Value
SH- 5	1.00	444073.21	1332219.64
US- 90A	1.00	823927.81	2471783.43
IH- 35E	1.00	581230.25	1743690.74

Table 15: Iteration: 4

S.No.	Utility	Assigned Value	Expected Value
SH- 5	1.00	444073.21	1332219.64
US- 90A	2.00	1647855.62	2471783.43
IH- 35E	1.00	581230.25	1743690.74

Table 16: Iteration: 5

S.No.	Utility	Assigned Value	Expected Value
SH- 5	1.00	444073.21	1332219.64
US- 90A	2.00	1647855.62	2471783.43
IH- 35E	2.00	1162460.49	1743690.74

Table 17: Iteration: 6

S.No.	Utility	Assigned Value	Expected Value
SH- 5	1.00	444073.21	1332219.64
US- 90A	2.00	1647855.62	2471783.43
IH- 35E	3.00	1743690.74	1743690.74

Table 18: Iteration: 7

S.No.	Utility	Assigned Value	Expected Value
SH- 5	2.00	888146.43	1332219.64
US- 90A	2.00	1647855.62	2471783.43
IH- 35E	3.00	1743690.74	1743690.74

Table 19: Iteration: 8

S.No.	Utility	Assigned Value	Expected Value
SH- 5	2.50	1108453.64	1332219.64
US- 90A	2.00	1647855.62	2471783.43
IH- 35E	3.00	1743690.74	1743690.74

#### 4.2.3.3 Expected Value

Assuming the costs associated with all the criteria for respective projects have equal importance, the expected value of each project is divided by the number of criteria to obtain the cost for each project (Table 20:).

Table 20: The Expected Value for Each of the Criteria

Projects	Safety	Cost	Traffic Congestion
SH- 5	444073.21	444073.21	444073.21
US- 90A	823927.81	823927.81	823927.81
IH- 35E	581230.25	581230.25	581230.25

#### 4.2.3.3.1 Priority Table

It is generated by assigning the weight to each criterion for each project according to needs of the transportation agency (Table 21:).

Table 21: The Priority Value for Each of the Criteria

Projects	Safety	Cost	Traffic Congestion
SH- 5	0.53	0.24	0.23
US- 90A	0.31	0.48	0.21
IH- 35E	0.27	0.43	0.30

#### 4.2.3.3.2 Assigned Value

Numbers in Table 22: are the assigned costs for each project per criteria. These values are generated from the Matlab simulation.

Table 22: The Assigned Value for Each of the Criteria

Projects	Safety	Cost	Traffic Congestion
SH- 5	444073.21	444073.21	220307.21
US- 90A	823927.81	823927.81	0.00
IH- 35E	581230.25	581230.25	581230.25

#### 4.2.3.3.3 Envy Value

Appendix 3 shows the “for loop” used in a Matlab framework. For loop has been utilized to calculate total envy. Basically, envy is the utility of one project minus the utility of another project. Table 23: shows the summary of FDM analysis. The first column is the utility value associated with all of the projects. For loop, pair-wise comparison of utility value was completed to obtain individual envy among projects. The Matlab outcome for individual envy is shown in Table 24:.

Table 23: Summary for FDM

Projects	Utility	Assigned Value	Expected Value
SH- 5	2.50	1108453.64	1332219.64
US- 90A	2.00	1647855.62	2471783.43
IH- 35E	3.00	1743690.74	1743690.74

Table 24: The Total Envy for Each Project

Projects	SH- 5	US- 90A	IH- 35E
SH- 5	0.00	0.00	0.50
US- 90A	0.50	0.00	1.00
IH- 35E	0.00	0.00	0.00

The result shows that some envy exists among SH 5 & IH 35 E, US 90 A & SH5, and US 90A & IH35 E. Therefore, envy cannot be eliminated completely but can be minimized.

#### **4.2.4 Analytical Hierarchy Process**

Analytical hierarchy process (AHP) is the final step in the process of prioritizing projects. It is utilized as the common analytical base to integrate results of the previous two methods and to rank projects according to their viability. As mentioned earlier, in decision-making, especially in transportation projects, conflicts are very common, as there are many criteria to consider such as technical, political, social, financial, and many more (base for AHP). The main reason for adopting AHP as part of research is to reinforce the decision-making process. Methods such as CBA cannot convert all non-tangible criteria such as political and social priorities into monetary terms. Hence, CBA alone is an inadequate method for project evaluation.

The analytical hierarchy process (AHP), developed by Saaty, frames a complex problem in a hierarchical structure with the goal (objective) on the top followed by criteria and alternatives (as shown in Figure 2:). It is very effective because it takes both subjective and objective thinking into consideration. In other words, it is more intuitive to the human mind (Zhang, Machemehl, & Ahson, 2004). Conceptually, AHP allows allocating ranking to different criteria and grouping them in pairs for pair-wise comparisons. The pair-wise comparison is the critical step of this method.



For our research, Super Decision software has been used to prioritize projects. This software is based on Saaty's formula. It is very difficult and complex to do the calculations manually. Therefore, the software has been used to make results more accurate and eliminate errors.

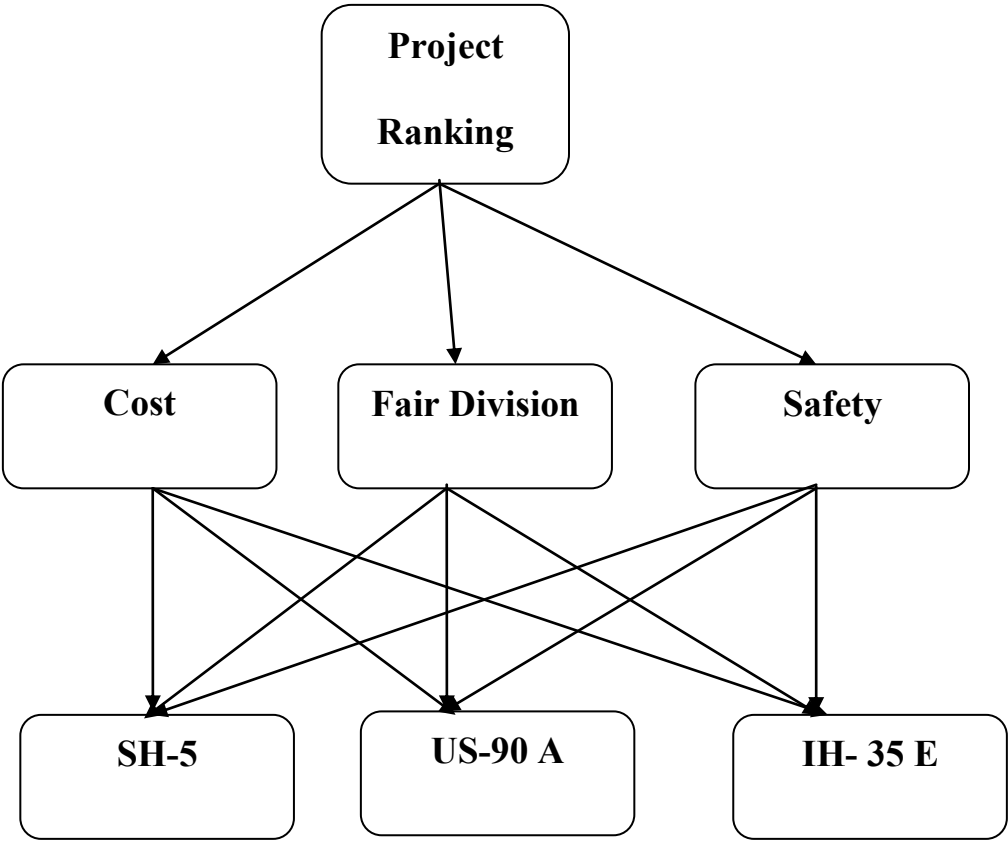


Figure 2: AHP Flow Diagram

As mentioned, the Super Decision software is based on Saaty's formula of pair-wise comparison. In this research, pair-wise comparisons between criteria and projects are

done. To give a better understanding of the procedure, a flow diagram is created (Figure 2:).

Elements from the second level hierarchy are compared with third level elements. Here, comparison means assigning a weight to criteria among two projects and comparing them. Figure 3: shows one of the pair-wise comparisons on the Super Decision. On the extreme left, a comparison criterion is a fair division. In the center are the projects comparison rows, which are comprised of a number scale (red and blue). On either side of each row are projects that are compared. In the first row, IH-35 E is compared to SH-5 with respect to the fair division. Numbers in blue on the left side of the row are to assign a weight to a project on the left, and red numbers are to assign the weight to a project on the right with respect to criteria. For research, weight is assigned under hypothetical conditions. Therefore, between IH-35 E and SH 5, importance has been given to SH 5 over IH 35 E w.r.t. fair division criteria. This means the fair division of funds is more important for SH5 compared to the other project to minimize overall envy. However, between IH 35 E and US 90 A, preference was given to IH 35 E under the same criteria. Similarly, the comparison between projects has been done w.r.t. other criteria; safety and cost (refer to Figure 3: to Figure 9:).

1. Choose		2. Node comparisons with respect to Fair Division		3. Results											
Node	Cluster	Graphical	Verbal	Matrix	Questionnaire	Direct									
Choose Node		Comparisons wrt "Fair Division" node in "Alternatives" cluster													
Fair Division		SH 5 is moderately more important than IH 35 E													
Cluster: Criteria		1. IH 35 E >=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. SH 5 2. IH 35 E >=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. US 90 A 3. SH 5 >=9.5 9 8 7 6 5 4 3 2 2 3 4 5 6 7 8 9 >=9.5 No comp. US 90 A													
Choose Cluster															
Alternatives		Normal Hybrid Inconsistency: 0.35331 <table border="1"> <tr> <td>IH 35 E</td> <td></td> <td>0.32204</td> </tr> <tr> <td>SH 5</td> <td></td> <td>0.53167</td> </tr> <tr> <td>US 90 A</td> <td></td> <td>0.14629</td> </tr> </table>					IH 35 E		0.32204	SH 5		0.53167	US 90 A		0.14629
IH 35 E		0.32204													
SH 5		0.53167													
US 90 A		0.14629													

Figure 3: Projects Comparison w.r.t Fair Division Criteria

### 1. Choose

Node Cluster

Choose Node

Safety

Cluster Criteria

Choose Cluster

Alternatives

### 2. Node comparisons with respect to Safety

Graphical Verbal Matrix Questionnaire Direct

Comparisons wrt "Safety" node in "Alternatives" cluster

SH 5 is moderately to strongly more important than IH 35 E

1. IH 35 E	>=9.5	9	8	7	6	5	4	3	2	2	3	4	5	6	7	8	9	>=9.5	No comp.	SH 5
2. IH 35 E	>=9.5	9	8	7	6	5	4	3	2	2	3	4	5	6	7	8	9	>=9.5	No comp.	US 90 A
3. SH 5	>=9.5	9	8	7	6	5	4	3	2	2	3	4	5	6	7	8	9	>=9.5	No comp.	US 90 A

### 3. Results

Normal Hybrid

Inconsistency: 0.69829

IH 35 E	<div style="width: 33%;"></div>	0.319
SH 5	<div style="width: 66%;"></div>	0.558
US 90 A	<div style="width: 11%;"></div>	0.121

Figure 4: Projects Comparison w.r.t Safety Criteria

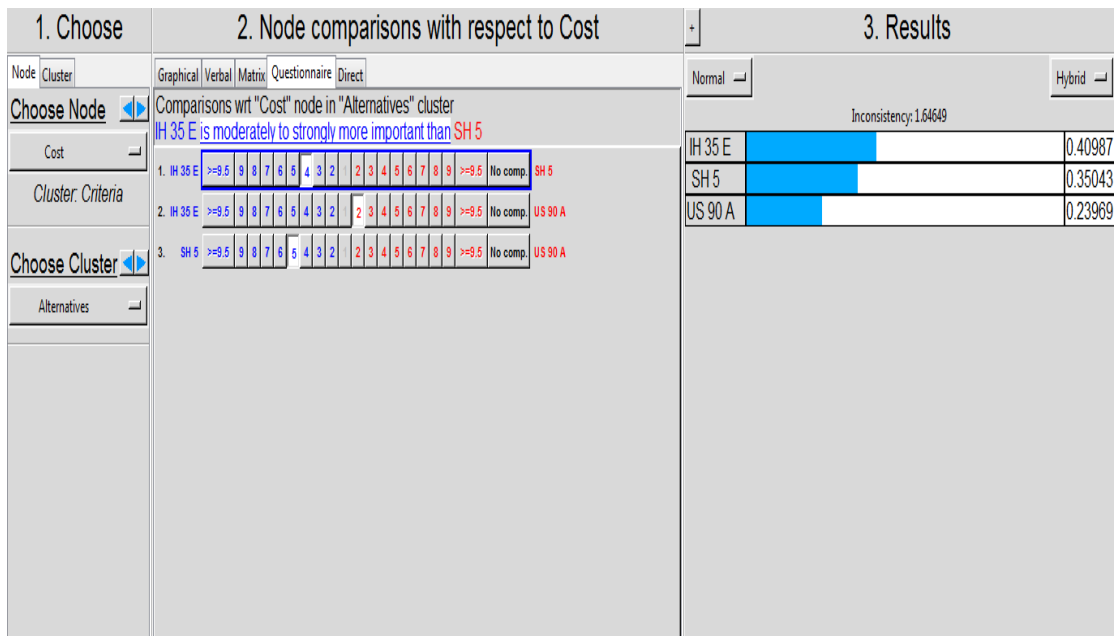


Figure 5: Projects Comparison w.r.t Cost Criteria

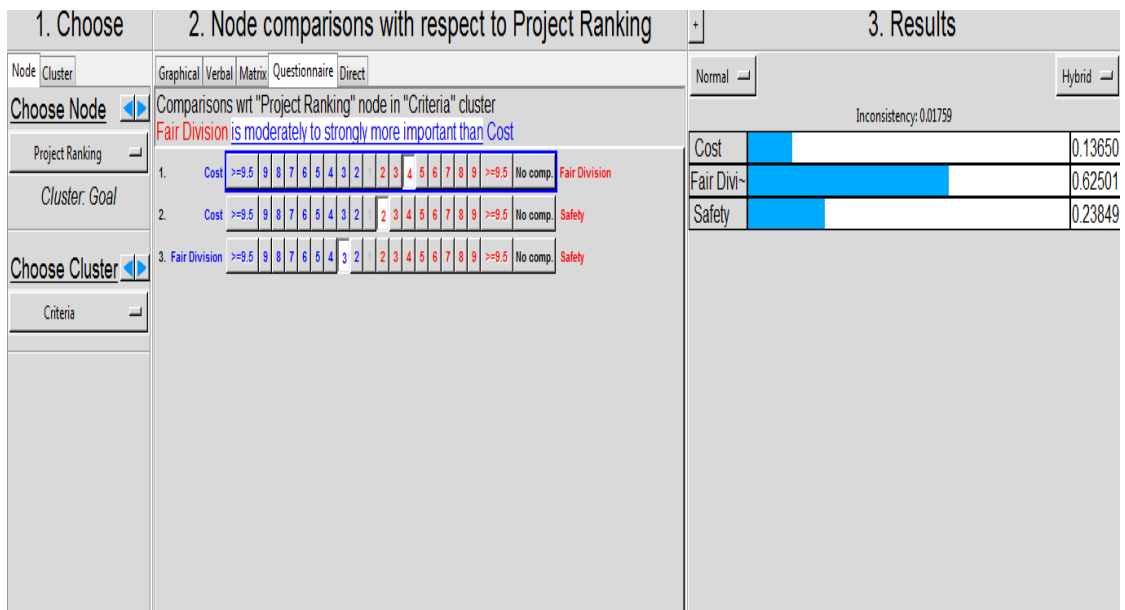


Figure 6: Criteria Comparison w.r.t Project Ranking



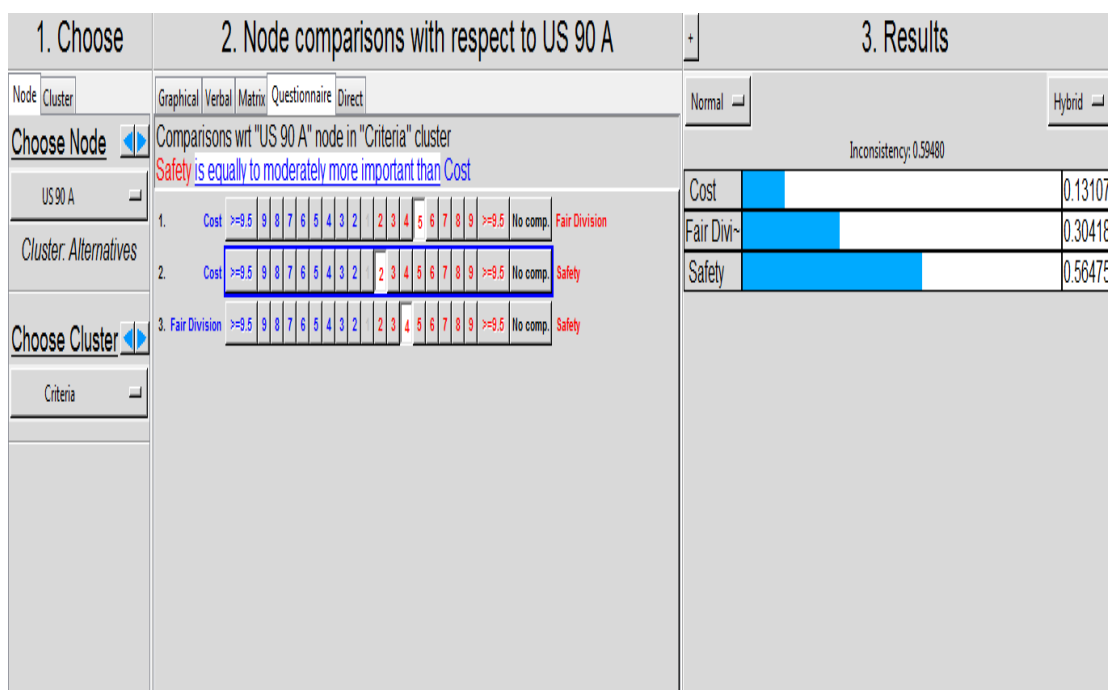


Figure 9: Criteria Comparison w.r.t Project US 90 A

To make results more accurate, comparisons of criteria w.r.t. to projects are also done. Now, all the criteria are compared on the number scale with each other w.r.t project (refer to Figure7: to Figure 9:). Table 25: shows the final ranking of all of the projects after the AHP analysis.

Table 25: Final Result for Each of the Projects

Alternatives	Total	Normal	Ideal	Ranking
SH 5	0.1702	0.5061	1.0000	1
IH 35 E	0.2531	0.3403	0.6723	2
US 90 A	0.0768	0.1535	0.3034	3

## **CHAPTER V**

### **RESULTS**

To allocate funds fairly and prioritize projects logically, research has utilized analytical methods step by step. Analysis and results of this research are summarized below.

#### **5.1 Summary of Results**

- From the cost-benefit analysis:
  - The accident savings for all the projects were converted into monetary benefits (refer to Table 9: ; i.e. present value; 2014 U.S. dollar value).
  - The present values, classified as benefits, are divided by respective cost of projects to calculate the benefit to cost ratio. Using B/C ratios, projects were prioritized (refer to Table 10:).
  - According to CBA, project IH 35 E should be carried out first, as it has more benefits attached to it, followed by US 90 A and SH5 respectively.
- However, CBA analysis takes only financial benefits into consideration and eliminates an aspect of fair division. Therefore, these projects are further analyzed to minimize envy using fair division
- Available funds are divided among proposed projects using the fair division algorithm, which was coded on the Matlab platform.
- The final result shows very little envy between the few projects. As evident from Table 24: , total envy counts to 2.0.

- There is some envy between SH-5 and IH 35 E, US 90- A and IH 35 E, SH-5 and US 90-A. Envy cannot be eliminated completely but can be minimized. This is what this research is intended to achieve.
- The final step is the analysis by AHP. Projects are finally ranked under three criteria: safety, fair division (i.e., less envy), and cost.
- The pair-wise comparison was done using AHP Super Decision software and ranked (Table25:).



## **CHAPTER VI**

### **CONCLUSIONS**

This research has attempted to build, test, and validate a custom quantitative model that reasonably allocates funds and prioritizes highway rehabilitation projects, based on critical decision-making criteria. Through an extensive literature review, shortcomings of existing practices were identified along with three independent potential analytical methods, which can be utilized to design a single effective analytical model to minimize envy and prioritize projects. Three real-time highway projects were selected from different locations in Texas and data associated with them was collected from the TxDOT database. Project information such as AADT, project construction cost, length (in miles), and crash rates that were gathered, was analyzed using CBA to assess financial viability of each project. A series of mathematical formulas were used to investigate the cost and benefits of the projects. To minimize envy and ensure fair fund allocation, FDM was employed where fair division and the sequential algorithm were simulated using Matlab. Finally, to integrate results of CBA and FDM and generate a common, robust result, AHP was incorporated using Super Decision software. AHP is a very simple method, which involves subjective analysis to rank and prioritize projects. Therefore, being a strong analytical tool, it has been adopted as the final method to integrate results from the previous two methods.

The results of this research indicate that according to financial viability projects were ranked in order: IH 35 E, US 90 A, and SH-5. Total envy obtained after fair division analysis is 2.0. Finally, when financial benefits and fair division were included as decision criteria along with safety as the third criterion, project ranking was changed to SH-5, IH 35 E, and US 90 A. This result implies that when other factors such as fair division and safety were also given equal importance in decision-making, the prioritization list of the project may change from what we get by just analyzing the financial viability of projects.

This research is intended to assist STAs and researchers in quickly, reliably, and efficiently prioritizing highway projects and fund allocation. This effort is the first of its kind undertaken for this specific objective. This research also highlights the use of independent quantitative methods together to achieve a common objective. The methodology and approaches applied in this research should be improvised and repeatable by other researchers. However, the author acknowledges some limitations of the model such as sample size and number of decisive factors, which may be specific to the model used. Future research is suggested to further verify the effectiveness of the model by increasing sample size and inducing factors that are more decisive.

## REFERENCES

- AADT. (2013). *National Road Authority: project appraisal guidelines*. Retrieved from <http://www.nra.ie/policy-publications/project-appraisal-guideli/Unit-16.1-Estimating-AADT-on-National-Roads.pdf>.
- Administration, F. H. (2011). *Roadway Safety Information Analysis: A Manual for Local Rural Road Owners*. Retrieved from [http://safety.fhwa.dot.gov/local\\_rural/training/fhwasaxx1210/s3.cfm](http://safety.fhwa.dot.gov/local_rural/training/fhwasaxx1210/s3.cfm).
- Albitres, C. M. C., Krugler, P. E., Ibarra, I., & Montes, E. (2012). *A dynamic programming optimization approach for budget allocation to early right-of-way acquisitions*. Paper presented at the Journal of the Transportation Research Forum.
- Annes, R., Carpenter, N., Hashmani, A., McGinnis, B. J., Parrish, M., Joshi, N. N., & Lambert, J. H. (2006). *Prioritizing highway construction with a benefits analysis*. Paper presented at the Systems and Information Engineering Design Symposium, 2006 IEEE.
- Chang, C. M., Montes, E., Taboada, H. A., & Espiritu, J. F. (2014). Fair division transportation allocation model for funding prioritization. *Journal of Infrastructure Systems*, 21(1), 04014030.
- Chang, C. M., & Montes, E. (2014). An optimization approach applied to fair division transportation funding allocation models. *A Message from the JTRF Co-General Editors* 3, 53(1), 101.
- Fuguitt, D., & Wilcox, S. J. (1999). *Cost-benefit analysis for public sector decision makers*. Greenwood Publishing Group.
- Gherghinescu, I. O., & Bandoi, a. (2010). Specificities of using the cost-benefit analysis for public projects financed by the structural funds. *Finante-provocarele viitorului (Finance-Challenges of the Future)*, 1(11), 236-242.
- Gonzalez, E., Liu, J., Liu, W., Zhang, Z., Murphy, M. R., O'Connor, J. T., & Bhat, C. (2013). An AHP-based approach to prioritizing resources for highway routine maintenance. *Report no. FHWA/TX-13/0-0-6623-2*.
- Godinho, P., & Dias, J. (2012). Cost-benefit analysis and the optimal timing of road infrastructures. *Journal of Infrastructure Systems*, 18(4), 261-269.
- Harberger, A. C. (2009, January). *Introduction to cost-benefit analysis, part IV, applications to highway projects*. Los Angeles, CA: University of California, Los Angeles.

- Kornhauser, L. A. (2000). On justifying cost-benefit analysis. *The journal of legal studies*, 29(S2), 1037-1057.
- Lee, D. (2000). Methods for evaluation of transportation projects in the USA. *Transport policy*, 7(1), 41-50.
- Mathur, S. K. (1996). *Public infrastructure investment decision making: Multicriteria trade-off optimization*. UMI
- Montes, E. (2014). *Using fair division methods for allocating transportation funds*. University of Texas at El Paso.
- Poor's, S. A. (2014). *US inflation rate by year*. Retrieved from [http://www.multpl.com/inflation /table](http://www.multpl.com/inflation/table)
- Tare, P. (2014). *Project prioritization through the use of cost-benefit and fair divisions analysis*. Texas A&M University
- Reddy, G. R. S. (2007). *Evaluating TxDOT'S safety improvement index—A prioritization tool*. Texas A&M University.
- Tanadtang, P., Park, D., & Hanaoka, S. (2005). Incorporating uncertain and incomplete subjective judgments into the evaluation procedure of transportation demand management alternatives. *Transportation*, 32(6), 603-626.
- Texas DOT, T. P. (2007). *2007 Statewide preservation program*. Retrieved from [ftp.dot.state.tx.us: http://ftp.dot.state.tx.us/pub/txdot-info/tpp/fundingcategories.pdf](ftp.dot.state.tx.us:ftp://ftp.dot.state.tx.us/pub/txdot-info/tpp/fundingcategories.pdf)
- Transportation, U. D. (2013). *Agency financial report*. Washington DC: US Department of Transportation.
- Transportation, M. d. o. (2015). *Benefit cost*. Retrieved from <http://www.dot.state.mn.us/planning/program/benefitcost.html>
- Transportation, U. D. (2013). *The FY 2014 president's request for the department of transportation*. Washington DC: US Department of Transportation.
- TxDot. (2012, January). *Protect selection process*. Austin, TX: Finance division: Texas Department of Transportation.
- Texas 2030 Committee. (2009). *2030 committee Texas transportation needs report*. Retrieved from [http://texas2030committee.tamu.edu/documents/final\\_022609\\_report.pdf](http://texas2030committee.tamu.edu/documents/final_022609_report.pdf).
- Transportation Funding (2012-2013). *Understanding State Road and Highway funding in Texas*. Austin, TX: Texas Department of Transportation.

U.S. Department of Health & Human Services. (n.d.). *Cost benefit analysis*. Retrieved from Centers for disease control and prevention, US Department of Health & Human Services: <http://www.cdc.gov/owcd/eet/cba/Fixed/4.html>

US DOT. (2010). *Benefit/cost analysis for transportation infrastructure*. Retrieved from A Practitioner's Workshop <http://tti.tamu.edu/group/tec/files/2011/09/benefit-cost10-proceedings.pdf>

Weiner, E. (1999). *Urban transportation planning in the United States: An historical overview*. Greenwood Publishing Group.

Zhang, Z., Machemehl, R. B., & Ahson, I. (2004). *Application of the analytic hierarchy process for prioritization of pavement data collection for the TxDOT PMIS*. Austin, TX: Center for Transportation Research, Bureau of Engineering Research, University of Texas at Austin.

## APPENDIX

```
%Data definition
cost_project1=1332219.64/3;
cost_project2=2471783.43/3;
cost_project3=1743690.74/3;
cost_divide_by3 = [cost_project1,cost_project1,cost_project1;cost_project2
exp_cost=cost_divide_by3;

initial_priority=[0.53, 0.24, 0.23; 0.31, 0.48, 0.21; 0.27, 0.43, 0.30];
priority = initial_priority;
initial_budget = 4500000;
budget = initial_budget;
assignment=zeros(3);
envy = zeros(3);

%Algorithm
stop_flag=0;
```

### Matlab Framework

```
while stop_flag==0,
    [M,I] = max(priority(:));
    [I_row, I_col] = ind2sub(size(priority),I);
    if budget > exp_cost(I_row, I_col),
        budget = budget - exp_cost(I_row, I_col);
        assignment(I_row, I_col) = exp_cost(I_row, I_col);
        priority(I_row, I_col)=0;
    else
        assignment(I_row, I_col) = budget;
        budget = 0;
        stop_flag = 1;
    end
    utility = assignment./exp_cost;
    utility = sum(utility,2);
    fprintf('iteration %d',iteration);
    summary = [utility,sum(assignment,2),sum(exp_cost,2)];
    table(summary(:,1),summary(:,2),summary(:,3),'RowNames',{'SH-5','US-90'}
    iteration = iteration+1;
end
```

### While Loop

```
[-] for i=1:3
[-]   for j=1:3
      if utility(i)-utility(j)<0,
          envy(i,j)=abs(utility(i)-utility(j));
      else
          envy(i,j)=0;
      end
    end
  end

TotalEnvyDistrict = sum(envy,2);
TotalEnvy= sum(TotalEnvyDistrict);
```

For Loop